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THE DEVELOPMENT OF DRAINAGE SYSTEMS AND THE DYNAMIC CYCLE.*

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INTRODUCTION.

The present study looks at streams from the dynamic viewpoint.[1] It goes without saying that the forces at work on the lands of the earth are just as important in physiography as are the results brought about by those forces.

The concept of age, applied to valleys in a geomorphologic sense, has been carried over on occasion and applied to streams in such a way as especially to emphasize change of velocity and its results. A stream is never young, never mature, and never old in a strictly dynamic sense, for the processes, although they vary in intensity, vary little if at all in quality. However, a general view of streams or a combination of them reveals a certain cyclic sequence of events which it is the purpose of this paper to trace in orderly fashion. This sequence of events has been called the dynamic cycle.

The first hints of the dynamic cycle were observed on a hillside during a rainstorm. A fairly flat surface on rather compact material passed through enough of a miniature drainage cycle from the beginning of interlacing rills to the formation of master streamlets to give a momentary glimpse of the various steps in the cycle. Nothing further was done with the idea until the problems presented by the drainage and the land forms of southeastern Ohio suggested that a return to, and an intensive study of, the fundamental characteristics of stream development might throw light on the origin and history of the

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*Presented before the Geological Society of America at Washington, D. C., December 28, 1929.

[1]Dual Nature of Physiography. Science, Vol. 72, 3-5, 1930.

drainage and also facilitate an understanding of the geomorphologic history. The present paper is one of the results of that study.

Subsequent field work included the further study of portions of the cycle passed through in miniature, and rather extensive observation during portions of four field seasons. The many different steps in the development of a drainage system may be observed separately on a large scale and later fitted together into an orderly sequence. Obviously the time required for the entire course of the cycle is too long to permit of direct observation.

An attempt has been made to follow the inductive method from the original observations to those made later and the whole tested and supplemented for synoptical reasons by map study. The United States Geological Survey topographic sheets of the eastern part of the country were consulted, about two hundred of the maps selected, and the drainage traced off. From these the illustrations here included were chosen to represent to a fair degree the sequence of events in the evolution of a drainage system. Maps of the late phases of the cycle were found in a region where the elevation of the level of base-level advanced the cycle sufficiently to give adequate illustrations.

The drainage cycle[2] falls naturally into two main sequential stages—extension and integration. Extension includes the sequence of events from initiation of the drainage system (in many cases the initiation of certain activities) until it, as a system or branchwork, completely occupies the basin. Integration includes the sequence of events from maximum extension to and through the emergence of master streams or master tributaries.

The scheme of development here presented will be given in a fashion as nearly ideal as possible, since departures or variations from the ideal for one reason or another will then be the more easily recognized and understood. The main body of the paper will trace the steps in the dynamic cycle and the discussions will consider some of the relationships between streams and their environment.

Assumptions and Definitions. — The initial assumptions include a certain uniformity of lithology, a simplicity of rock

[2]A summary view of the nearly ideal cycle appeared in the Geographical Review, July, 1931.

structure, and a humid climate like that of the eastern United States.

Any stream or branchwork of streams with a common point of discharge constitutes a drainage system. Rainwash from the dynamic standpoint includes all rain water that has not concentrated into definite streams which, after such concentration, form an organized part of a stream system.

The vertical distance through which rainwash travels on the ground is called the drainage relief and the ratio of the vertical to the horizontal distance covered at the same time is called the drainage ratio.

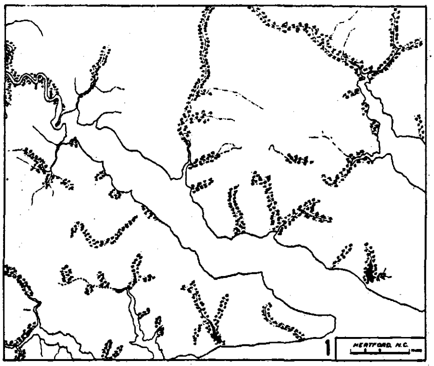
Acknowledgments.—The writer wishes to acknowledge his indebtedness to the Research Committee of the Graduate School of Ohio State University for a grant of funds with which he secured a research assistant to aid in the office work and the preparation of maps. He is also indebted to the Geological Department of Yale University, the Ohio Geological Survey, and the Department of Geology of Ohio State University for the use of maps and for office supplies. Sincere thanks are due these several organizations.

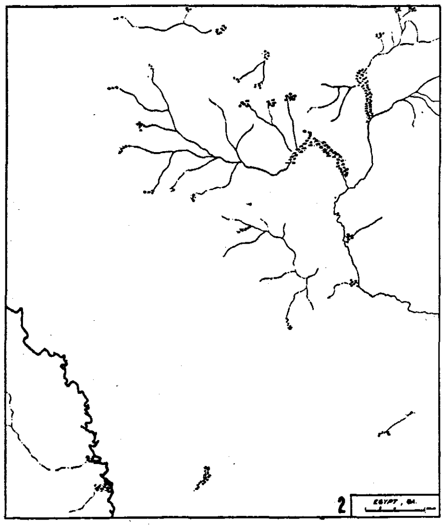
EXTENSION.

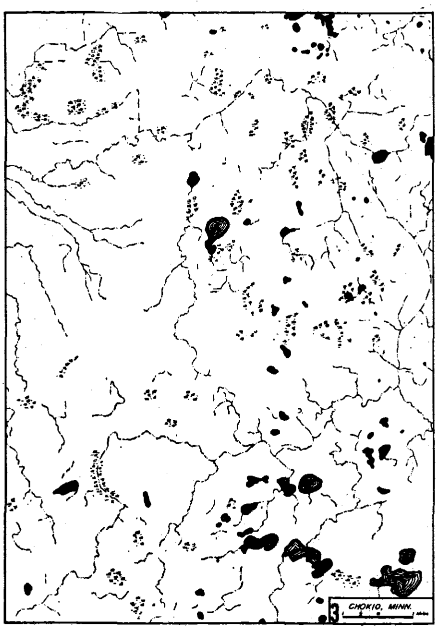
Initiation of the Drainage System.—The early and the late phases in the cycle are perhaps the most difficult of all to observe, to find on maps, and to picture mentally. Small scale observations give the best results, although on a very small area rainwash tends to overshadow the concentration of water into rills.

Figure 1 indicates what may be expected at the start of extension when drainage begins to be concentrated along definite paths. A number of the streams end without uniting into, or joining, a main, and swamps in some cases conveniently mark the courses of future streams. A large percentage of the surface lacks conspicuous channel-ways for the disposal of rain water. Though the coast has been drowned and the ground water surface has been elevated, yet the hints concerning the initiation of a drainage system appear clearly.

The streams on Figure 2 show a better degree of organization than those on Figure 1; they also show the disappearance in large measure of the indecision and hesitancy of pre-extension. Essential features of the future system have become apparent, although a few streams still end indefinitely. The blank







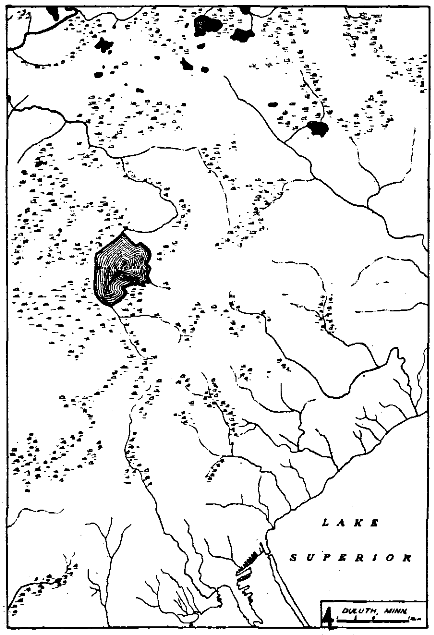


FIG. 1. The initiation of drainage systems; almost pre-extension for the most part.

FIG. 2. The start of dendritic extension. Swamps occur on uplands and lowlands. The probable role of swamps as indicating the courses of future streams is well shown on the central north-south strip of the Folkston, Georgia-Florida, topographic map.

FIG. 3. The first efforts toward organization and extension on a recently glaciated surface.

FIG. 4. The start of elongation. Poor organization. Both headward and mouthward elongation.

areas contain numerous shallow linear swamps which as features preceding actual streams are particularly well shown in the central part of the Folkston, Georgia-Florida, map.

Some parts of the Chokio, Minnesota, sheet (Figure 3) show the first efforts of the run-off to concentrate along definite paths, the first efforts toward organization on a recently glaciated surface. The inland part of the Duluth map (Figure 4) shows much the same condition save that, the topographic details being less minute than on the Chokio sheet, the initial stream courses are far less numerous, and hence the advance of the drainage cycle appears to be less rapid but more systematic.

Discussion.—Although rainwash dominates the time particularly before and during initiation, most of the land surface of the earth never leaves the rainwash stage. It is the task of a drainage system during extension to reduce the horizontal distance of rainwash travel to as small an amount as possible. From an areal standpoint, therefore, rainwash possesses far more importance than the streams to which the water is contributed.

The discovery of an ideal beginning for a drainage system, were such a thing possible, would be of great interest and utility. Four methods of origin come to mind: (1) headward growth of streams from what is commonly called the "gully stage," (2) the headward and mouthward growth and union of indefinite stream-ways into a unified stream discharging into another stream or body of standing water, (3) mouthward growth, and (4) combinations of the first three. The streams emptying directly into Lake Superior on Figure 4 appear to illustrate method (1), as do those on the north portion of Figure 5 neglecting drowning. The making of a hillside gully is a very common illustration of the first method, but many such gullies actually constitute in the end a phase of stream development by the second method.

The origin of a valley and the origin of a stream may differ to a considerable degree if the two be divorced temporarily. Part of the rain falling on a uniformly sloping area forms the run-off which attains sufficient volume to make definite streams long before the edge of lowest elevation is reached. At some place between the higher and lower edges, but closer to the upper, streams will normally begin.[3] Conspicuous gullies,

[3]See for instance: Marr, J. E. The scientific study of scenery. London, 1926. Pp. 72-75. Wentworth, C. K. Principles of stream erosion in Hawaii. Journ. Geol., Vol. 36, 398. 1928.

in contrast, tend to form at the lower edge and thence lengthen upstream in such fashion as to produce a break in the longitudinal profile of the valley. Profile breaks like these testify to a certain lack of simultaneity in the origin of a stream and the origin of a definite valley. They are by no means uncommon features and of course come to mind at once in relation to rejuvenated streams. A topographical and historical analysis of the short streams to Lake Superior on Figure 4 reveals the fact that their mouths have been elongated by lowering of the lake level (method 3) and their heads have been lengthened partly by means of method (1) and partly by means of method (2). In truth, the question may be raised whether any stream branching away from a main ever attained full size solely by wash at the gully head or, for that matter, by any single method of growth.

The streams on the remainder of Figures 4 and 5 and also those on Figure 3 subscribe to method (2) in origin. Rain falling on a new land surface seeks out all low places and the discovery of sloping linear depressions permits the formation of incipient streams. The union of such embryonic streams with each other or with an established waterway marks the origin of a definite stream (but not necessarily an erosional valley in entirety) and the beginning of the stage of extension.

In conclusion it may be said that many local streams and small tributaries have with little doubt been started from the "gully stage," though the gully is far more important in the history of a valley than in the development of the stream; and that most of the larger streams and the chief parts of drainage systems have originated in a more complex fashion than implied in the development of a gully.

Initiation on the whole is a time when such streams as do exist lack organization, when hesitation and indecision rather than systematized invasion of the land governs the run-off, and when rainwash overshadows all other processes. Initiation refers not only to the beginning of streams but also, and more especially, to the beginning of extensional activities. A continuation of these activities constitutes the stage of extension.

Elongation of Streams.—Elongation refers to all manner of stream lengthening. The first hints of systematic elongation indicate the existence of extension. Two directions of lengthening may be observed: headward into unoccupied land inherited from a formative agency, as glaciation, and mouthward over a newly emerged area.

All maps in the first part of the paper show elongation of one type or another. The main streams on Figure 6 not only show headward elongation, but also suggest the possibility of future competition which will arise because of such elongation. Additional examples may be seen on Figures 1, 2, 4 and 5.

Growth in the opposite direction, mouthward, is much less emphasized in geologic literature and less well developed in our ideas of stream history. Mouthward elongation has been called "progression" by Doctor W. Armstrong Price,[4] the progressive river being one "which grows outward across a rising coastal plain." However, the type of lengthening here considered is far more general in application, referring to all lengthening accomplished in the mouthward direction as the following examples indicate. The streams flowing into the Glacial Lake Agassiz lengthened mouthward as the lake contracted and withdrew to northward. Figure 7 shows the result at one locality. Such direction of growth was not always exactly parallel to the older part of the stream; in some cases the elongated portion made high angles with the original course[5] or even reversed its direction.

In fact mouthward elongation has been very common in the areas contiguous to the Great Lakes. Postglacial streams, independent of preglacial channels,[6] now flow over the beds of glacial lakes into the present Lake Superior, having entered Lake Duluth and successively afterward, Lake Algonquin and the Nipissing Great Lakes prior to the existence of Lake Superior. St. Louis River likewise lengthened its lower course[7] to follow the receding waters of Lake Duluth. The streams along the western and southern margins of Lake Erie have had the same history, illustrated in one case by the Fremont, Ohio, sheet (Figure 8).

Elongation serves to get the stage of extension under way, to produce a skeletonized drainage system, and by so doing, to eliminate the initial abbreviated streams.

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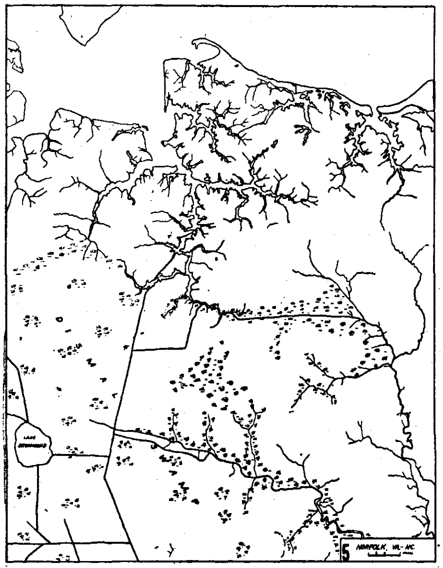
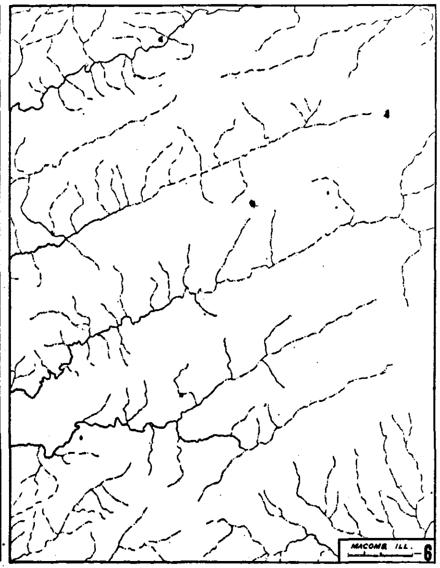
[4]Personal communication, March 26, 1930.

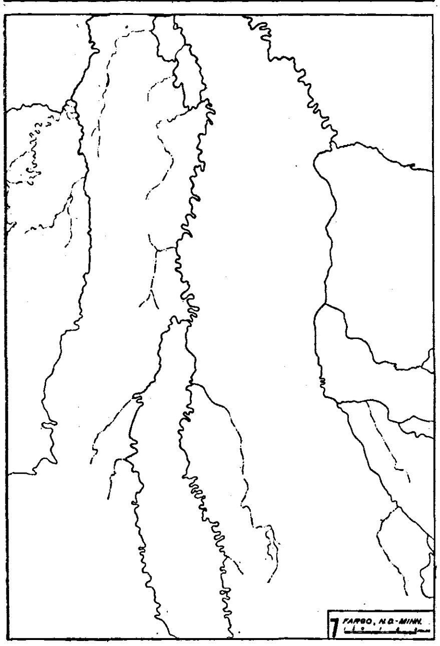
[5]Upham, Warren. The Glacial Lake Agassiz, U. S. Geol. Survey, Mono. 25, 19–20, 54–57; Pls. 3 and 25. 1896.

[6]Leverett, F. Moraines and shore lines of the Lake Superior region, U. S. Geol. Survey, Prof. Paper 154-A, 8. 1929. Plate 2 shows the many short streams entering Lake Superior.

[7]Ibid, 10.







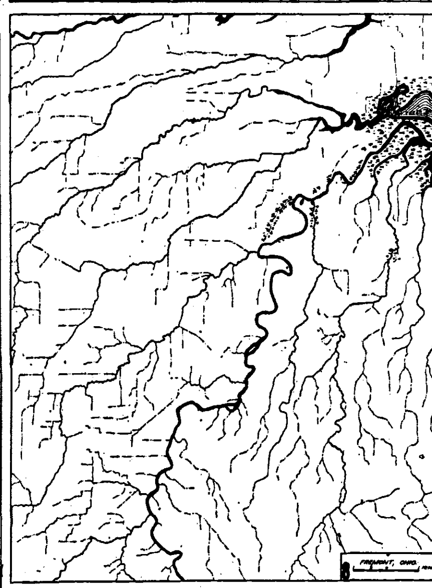


FIG. 5. Early extension and headward elongation.
Fig. 6. The stage of extension on a drift plain; elongation fairly complete, elaboration started. Parallel headward elongation.
FIG. 7. Early extension on a lake plain. Parallel mouthward elongation. Elaboration barely begun.
FIG. 8. Mouthward elongation over a lake plain.

Discussion.—The word "extended" has been applied[8] on several occasions to rivers lengthened mouthward. Since the term does not enjoy common usage, its application, in the altered form "extension," has been broadened for use in connection with the first stage of the dynamic cycle, and the more simple designation lengthening, or elongation, employed for linear growth.

Mouthward lengthening and shortening undoubtedly have played an important part in the geologic history[9] of streams. A well-known example is the gradual growth of Mississippi River from southern Illinois to the present Gulf of Mexico. A case of equal if not greater interest lies in the growth of streams which follow a sea retreating out over a rather uniform slope. The arrangement[10] of the main streams on the Piedmont Plateau suggests the hypothesis that they have evolved in much the same fashion as those on the Atlantic Coastal Plain whose growth taken algebraically has been mouthward incident to a receding shore line. Consequently, the coastal plain sediments,[11] of whatever thickness, may once have extended over much if not all the Piedmont Province. At least an analysis of the drainage in the large suggests such an hypothesis applied here, however, only to the streams of the Piedmont. The case of the Potomac and the Susquehanna where they cross the mountain and valley belts does not appear with equal clarity from the present study.

Mouthward elongation deserves to be ranked along with headward and it is only just in view of the facts to consider them of equal importance. This much may be ventured as a tentative opinion: that mouthward elongation of the trunk

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[8]Davis, W. M. Geographical Essays. Boston, 1909. P. 181. Grabau, A. W. Textbook of Geology. Boston, 1920. Part I, p. 712. Cotton, C. A. Geomorphology of New Zealand. Wellington, 1922. P. 70.

[9]Some recent publications of significant interest are:

Adams, George I. The course of the Tennessee River and the physiography of the southern Appalachian region. Journ. Geol., Vol. 36, 481–493. 1928.

Adams, George I. The streams of the coastal plain of Alabama and the Lafayette problem. Journ. Geol., Vol. 37, 193–203. 1929.

Flint, Richard Foster. Pleistocene terraces of the Lower Connecticut valley. Bull. Geol. Soc. Amer., Vol. 39, 980–981. 1928.

[10]See Chamberlin and Salisbury. Geology. New York, 1906. Vol. 1, p. 168, Fig. 160, or a drainage map of the United States. Also, Cotton, C. A. Geomorphology of New Zealand. Wellington, 1922. Pp. 69–70.

[11]Doctor D. W. Johnson, at the Toronto meetings of the Geological Society of America, December 30, 1930, presented the theory that the coastal plain sediments formerly may have extended 125 to 200 miles farther northwestward than they do now.

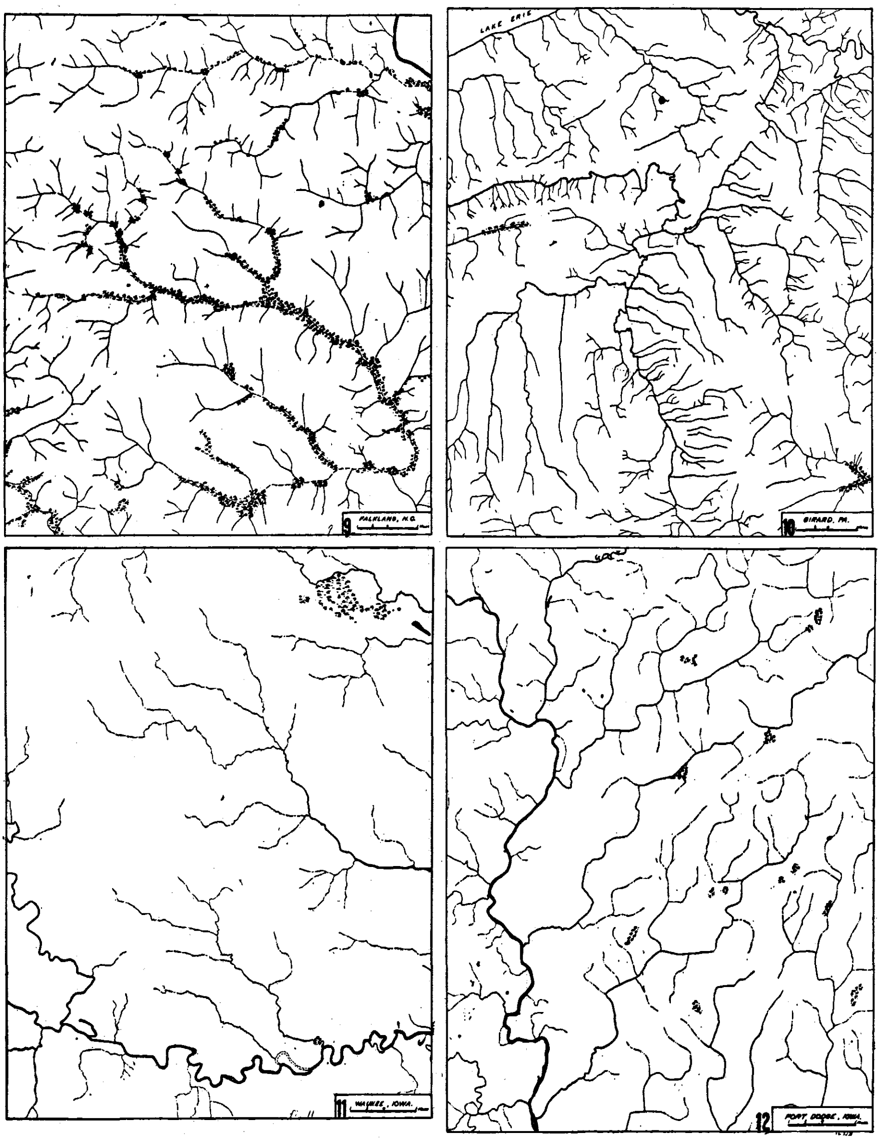


FIG. 9. Dendritic elongation and extension.

FIG. 10. A study in direction and pattern of elongation, showing mouthward and headward direction of lengthening as well as parallel and dendritic patterns.

FIG. 11. Elongation incomplete; elaboration scarcely started. Chiefly Wisconsin drift. Figs. 11–14 show the progress of elaboration.

FIG. 12. Elongation almost complete; elaboration started. Wisconsin drift.

portions of a drainage system has far more importance in the history of such a system than has headward elongation considered over a region and over a period of time.

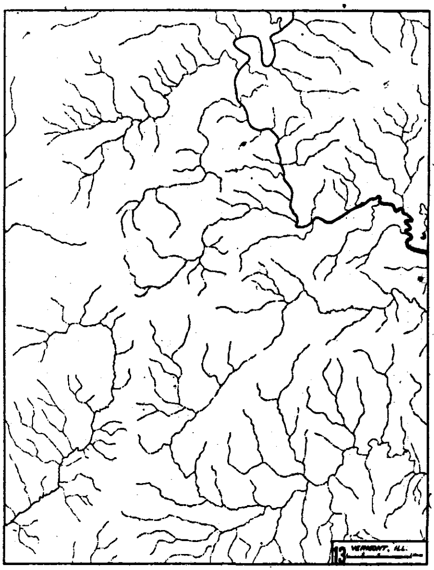
Headward elongation is most aggressive where there is an optimum amount of slope and uniformity of surface. A surface like that on the Chokio quadrangle is inimical to steadily progressive and rapid headward growth. On the other hand, if the slope is too steep, headward growth apparently is retarded, as for example on the Allegheny ridges. The cause for the retardation lies among several factors such as thinness of soil, ground water surface, vegetation cover, nature of the rock, and the gradient of the run-off, all of which seemingly conspire to deliver the water in concentrated form at a comparatively low elevation on the mountain side. There must be some optimum slope and surface.

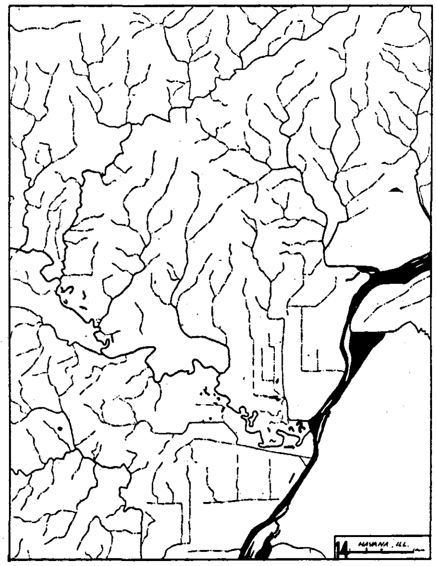
The subject of stream lengthening is complicated and perhaps merits more discussion than space permits. It is worthy of mention from the historical standpoint, however, that many streams undoubtedly have been lengthened headward following a waning ice sheet. An interesting study of stream growth in a mouthward direction may be made along shores as the waves recede and the tide goes out.

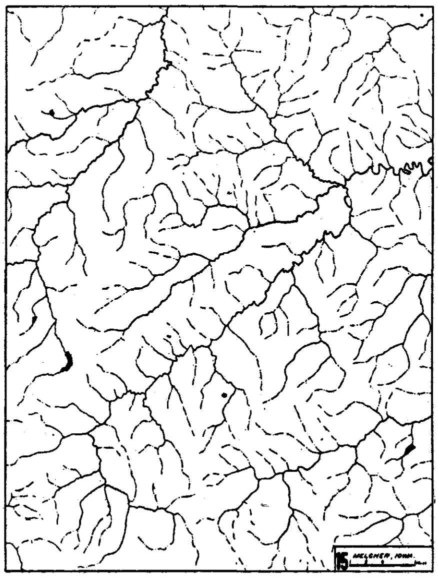
Elaboration of the System.—Elaboration refers to the constant development of minor tributaries which fill in the main body, or framework, of the growing system. The initially elongated system is expanded and embellished internally.

The Fargo map better than any other shows elongated streams with a minimum addition of tributaries. Elaboration may be followed as a progressive affair on the series of maps, Figures 11, 12, 13, 14, and 15, so chosen as to represent approximately the same relative positions with respect to the particular drainage systems. On the Waukee sheet the process of elaboration has just begun, whereas on the Melcher the branchwork of streams is fairly complex, most of the surface has been invaded, and the process therefore is approaching completion.

Elaboration eliminates the skeletonized form produced by elongation. The process constantly adds tributaries of decreasing rank until the branchwork, as a system of drainage, is fully elaborated. A system may be considered full-grown when it fulfills certain requirements discussed subsequently under the topic maximum extension.







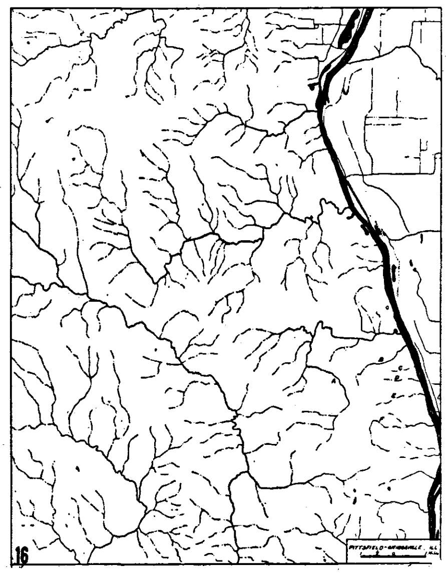


FIG. 13. Elongation practically complete; elaboration well begun. Illinoian drift.

FIG. 14. Elongation done; fairly well elaborated. Illinoian drift.

FIG. 15. Elongation done; elaboration far along. Kansan drift.

FIG. 16. Territorial aggression. Stream A is the aggressor. Streams B, C, D, E, and F have been repressed. Stream F is submissive. Stage of extension.

Discussion.—Elongation and elaboration constitute the stage of extension; the two seldom can be separated save for mental convenience. Local elongation, however, must precede the addition of tributaries at any particular place. On the whole, lengthening applies equally as well to individual streams as to systems while elaboration can refer only to an entire system or a unit part of one. A stream or system once established must in the nature of things always continue its efforts to lengthen and expand, at least as long as the laws governing extension remain in operation. This apparently must be so, since extension is typified by the attempt to shorten the distance of rainwash travel. Competition arises not only among streams but also among drainage systems because of the inexorable desire to grow, and the satisfying of this desire carries the activities of extension, though not the stage itself, over into the stage of integration.

Perhaps the series of maps, Figures 11 to 15, deserves a further remark: the older drift sheets possess the more elaborate drainage systems, which alone would occasion no comment were it not for the fact that these particular maps were placed in sequence quite without forethought while a large number of maps were being analyzed and arranged in order. They were selected because of their closely similar positions in their respective drainage systems and only then were the particular drift sheets determined.

Pattern of Extension.—The patterns assumed by stream systems because of extension will be mentioned only in so far as a simplified analysis of the stage requires; the complete sequence of pattern development will not be considered. Maps such as shown on Figures 6, 7, and 8 illustrate parallel elongation, a very common type apparently if extension is in its early phases, or if the initial surface is of rather uniform nature and of definite slope, or if elongation occurs in a mouthward direction. (Of course the parallel pattern also develops under structural and lithologic control.) The influence of surface and slope becomes apparent in a study of the shoe string type of rills. The parallel arrangement develops gradually into a parallelo-dendritic pattern in absence of structural control and the original pattern may be restored in the main by blotting out the branchwork of tributaries fastened onto the mains.

The dendritic is the contrasted type of pattern which develops because of the nature of the surface, the regional slope (or absence of it), and the materials. Figures 1, 2, 3, the north part of 4, and 5 show this type of extension on various surfaces. On figure 9 the dendritic pattern of lengthening applies equally well to different tributary groups.

Discussion.—A mention of dendritic pattern suggests the word "insequent" as used by Davis to[12] designate so-called self-guided streams, i.e., expanding stream systems controlled neither by initial slope, nor by difference of rock resistance, nor by structure.[13] Is this, however, a true lack of control even though the influence does not seem so definite as in the case of structurally controlled streams? In any case, insequent expresses a relation between surface and drainage and, though there is probably nothing fundamentally wrong with "insequent pattern," yet the word dendritic is much more generally used.

Although the dynamic viewpoint recognizes two fairly distinct types of pattern, the fact remains that variations and combinations of the two exist because of the influence of surface and material. Figure 10, illustrating not only both directions of elongation but also both patterns, furnishes a highly interesting study of surface form in relation to stream development from the short tributaries entering Lake Erie to the parallel streams in the southwest one-quarter of the map flowing down the back slope of a morainic ridge.[14]

Behavior of Streams During Extension.—A study of streams during extension reveals two contrasted types of behavior, *permissive* and *aggressive*. Permissive refers to the type whereby a stream or system extends into territory rightfully belonging to it in the course of natural development—that territory which it would be expected to occupy because of its position and relations. Each system develops normally in all its parts and drains a basin acquired by minimum encroachment on adjoining systems. Permissive behavior borders on the ideal since it requires fair play and an equitable distribution of territory, obviously a behavior calling for an unusual uniformity of surface, slope, material, and distribution of streams.

[12]Davis, W. M. Geographical Essays. Boston, 1909. P. 174.

[13]For these controls see: Tarr and Martin. College Physiography. New York, 1920. P. 186. Grabau, A. W. Textbook of Geology. Boston, 1920. Part 1, p. 712. Lahee, F. H. Field Geology. New York, 1916. Pp. 336–339. Tarr and Martin say: "This insequent stream pattern is often treelike, for which reason the drainage is said to be dendritic."

[14]Leverett, Frank. Glacial formations and drainage features of the Erie and Ohio Basins. U. S. Geol. Survey, Mono. 41, plate 15. 1902.

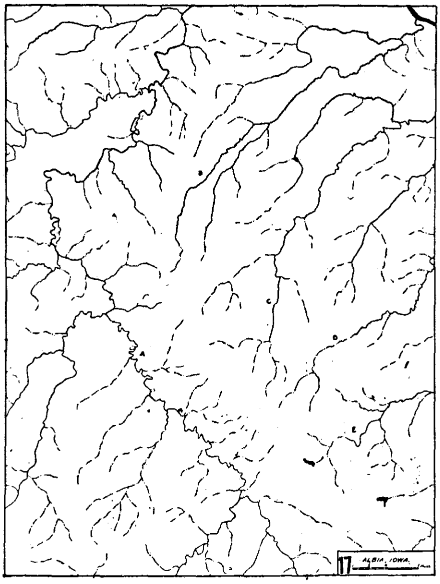
The early phases of extension, to be sure, witness the permissive type of behavior to a much more perfect degree in the normal order of events than do the late phases. A study of ideal behavior has certain value for, if a drainage system is chosen at random and superimposed upon a chart showing the same system developed under ideally permissive behavior, any accidents, variations, or abnormal development may be detected. This can be done in very simple fashion with Figure 24.

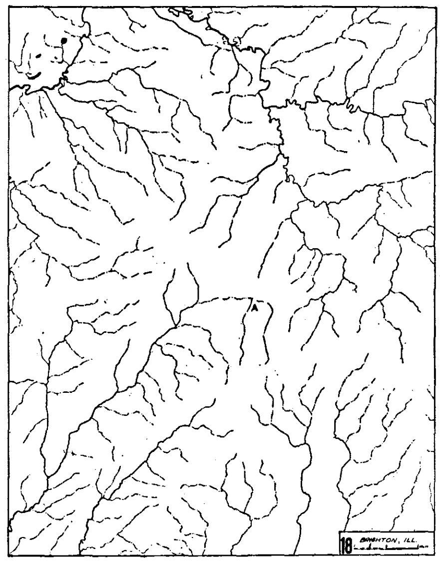
Aggressive extension refers to the behavior by which foreign territory or neighboring streams are captured. Hence, there may be aggression (1) as to territory and (2) as to streams.

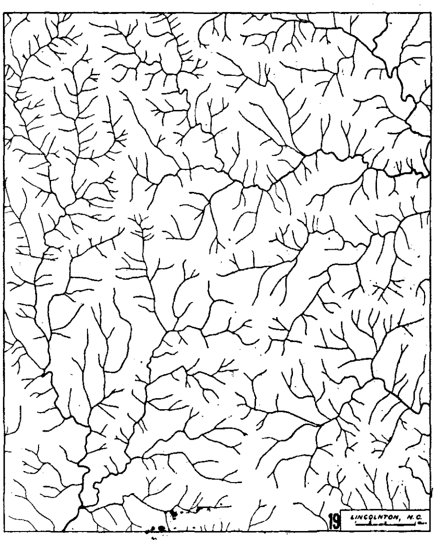
(1) On Figure 16 stream A has entered territory which belongs on general principles apparently to streams B, C, D, E, and F, and for that reason A is the aggressor. Streams B, C, D, and E have been repressed. Stream F is submissive because it has continued to grow, in a *different direction*, after repression. On figure 17, B, C, D, and E have been repressed by A. The principles governing aggressive and permissive extension will permit an interesting study of drainage behavior on the maps so far mentioned.

(2) Aggression with respect to streams is simply piracy as commonly understood. The type of piracy depends upon the impelling reason for the behavior; for instance, extension piracy has occurred on figure 18 at A. Since the larger streams crossing a barrier of resistant rock will cut down rapidly, tributaries to them will behave aggressively with respect to the smaller streams crossing the barrier and steal their headwaters. The smaller streams have been beheaded by the aggressive activities of the larger.

Discussion.—A realization that streams can be studied from the standpoint of behavior gives a clearer understanding of stream history in certain cases and a different method of approach to the study of land forms. Stream systems possessing obvious irregularities either have departed from a previous ideal scheme of development or are themselves more or less notable departures because of special initial, or inherited, conditions of the basin, and hence normal to those special conditions. Field observations should in most cases be the decisive criterion of differentiation. In any case, a concept of the ideal system and a knowledge of the variations will aid materially in deciphering the history of a system, in reconstructing the original surface, or both.







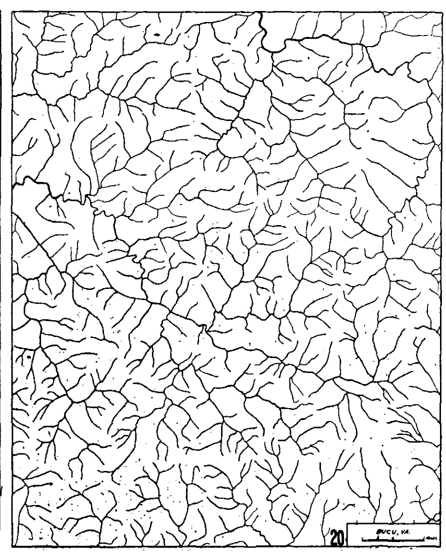


FIG. 17. Territorial aggression on a larger scale than on Fig. 16. Stream A, the aggressor, has repressed streams B, C, D, and E. Stage of extension.

FIG. 18. Aggression with respect to streams. Extension piracy has occurred at A. Extension well along.

FIG. 19. Maximum extension on the inner Piedmont Plateau. Coarse texture.

FIG. 20. Maximum extension on the Appalachian Plateau. Medium texture.

Although there are reasons for thinking that aggressive extension is a more normal affair than permissive, a knowledge of the latter facilitates an understanding of the methods, results, and relations of aggression. Very little if any aggression occurs during the initiation of a drainage system but it waxes greater as extension progresses and reaches a maximum as contiguous systems approach full development. Territorial aggression attains a maximum sooner than stream aggression.

Maximum Extension.—A system reaches maximum extension when elongation and elaboration have been completed—when the territory rightfully belonging to the system has been completely occupied. Active competition with contiguous systems, if such occurs, must therefore come for the most part after the attainment of maximum extension.

Figure 15 has the best developed drainage of any map among those so far given. Several varieties of maximum extension are shown on Figures 19, 20, 21, and 22, among which Figure 19 is slightly less well developed than the remaining three. The Lincolnton map is taken from a region of moderate relief on the inner Piedmont Plateau; the Bucu from a region of rather high relief on the Appalachian Plateau; the Prince Frederick from an area of low relief on the west shore of Chesapeake Bay; and the Ironton from an area of moderate relief near the west border of the Appalachian Plateau. The last two possess a fine texture.

Maximum extension is characterized by a lack of intermittent streams and by the presence of fully elaborated systems. It is first attained when the territory comes to be fully occupied by streams.

Discussion.—Extension is the stage wherein each system is impelled by the desire to shorten the distance of rainwash travel as much as possible by the lengthening of existing streams and by the addition of tributaries. In other words, extension is a process which attempts to increase the so-called drainage ratio until it reaches the maximum possible, that is, unity under ordinary circumstances, or a 45 degree slope. Exceptional slopes may, of course, be steeper. Nevertheless, this fixes mathematically and dynamically the time when maximum extension is attained at any locality, and an algebraic average applies to a system as a whole.

The query may arise as to whether any aggression either in respect to territory or to streams should be included within

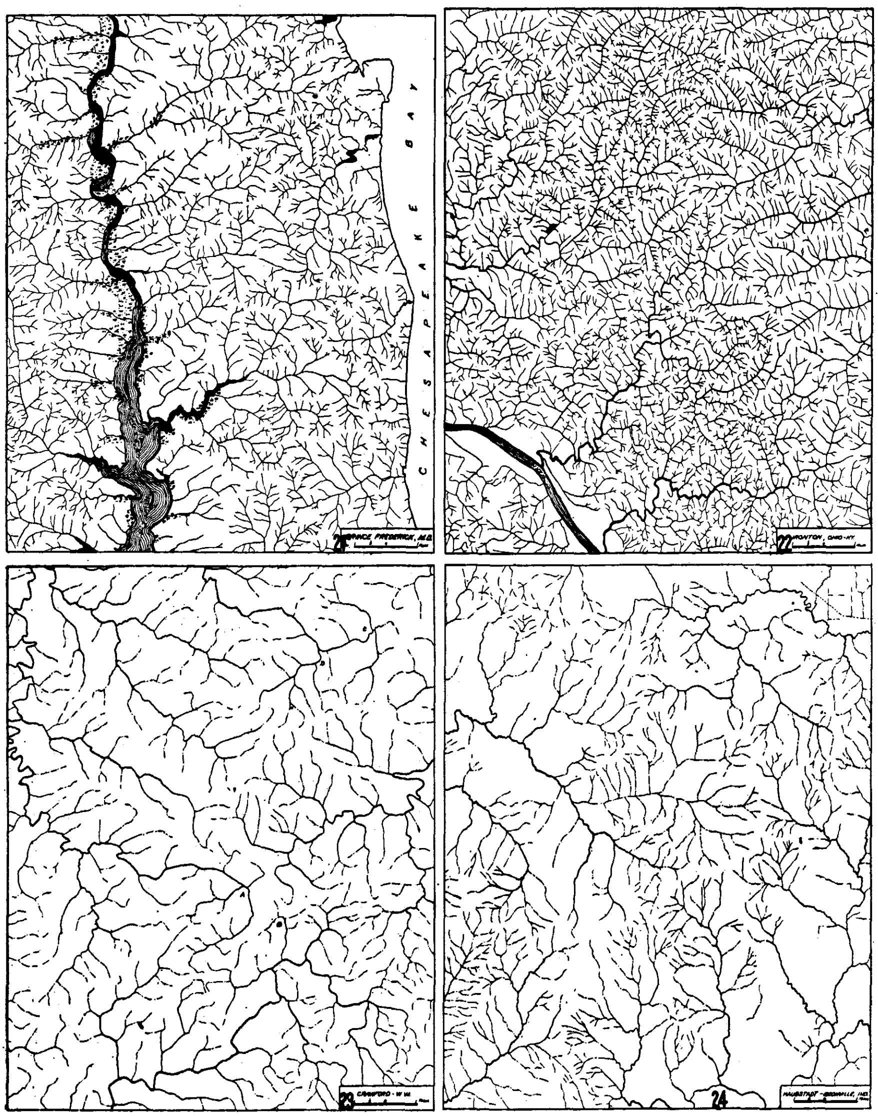


FIG. 21. Maximum extension along west shore of Chesapeake Bay. Fine texture.

FIG. 22. Maximum extension at west border of Appalachian Plateau. Very fine texture.

FIG. 23. Maximum extension definitely past. The piracy at A, B, C, and D indicate that the systems had been fully extended prior to the present. Intermittency has returned.

FIG. 24. Early integration. Abstraction and absorption started.

the limits of the stage of extension. When a drainage system in a given region first and fully drains that region then the *stage* of extension has attained maximum. The climax of competitive aggression therefore occurs after the complete occupation of the drainage basin. Such a concept appears logical because of observation, because of its simplicity and utility, and because of the nature of the dynamic scheme. A map will serve as an illustration of the point. The piracy, as at A, B, C, and D, Figure 23, gives evidence that the territory had been completely occupied at some time in the past and for that reason the system is now post-maximum extension.

Maximum extension also represents the transition from extension to integration. At times maximum extension is a very brief interval; at others it is of considerable length. If the interval be long the dynamic cycle appears to include three stages rather than two. However, drainage systems considered dynamically pass through two distinct stages only—extension and integration—which account for practically all of the activities. Some activities may well occur after maximum extension is attained, but before integration becomes *evident.* The trunk areas of a system in a region of small drainage relief begin the processes of integration with little doubt long before the outlying parts of the system have finished extension.

No reference has yet been made to the change from intermittent to permanent streams during the progress of extension. If the maps are viewed in sequence it will be seen that intermittency disappears headward as extension progresses, that it is entirely absent at maximum extension, and that it reappears especially among tributaries with the progress of integration. This change of character, which is essentially a change of relationships, depends largely upon the depth, shape, and gradient of the ground water surface, the variation in the amount of run-off discharged to streams, and the depth of soil cover. During extension the ground water surface characteristically lies below the valley bottoms of many tributaries. All streams, however, apparently intersect the surface at maximum extension, a time when that surface possesses its steepest gradients and greatest local variations in altitude. With the progress of integration the ground water surface appears to be lowered and flattened. Decreasing rainfall incident to decreasing elevation in a region of initially high

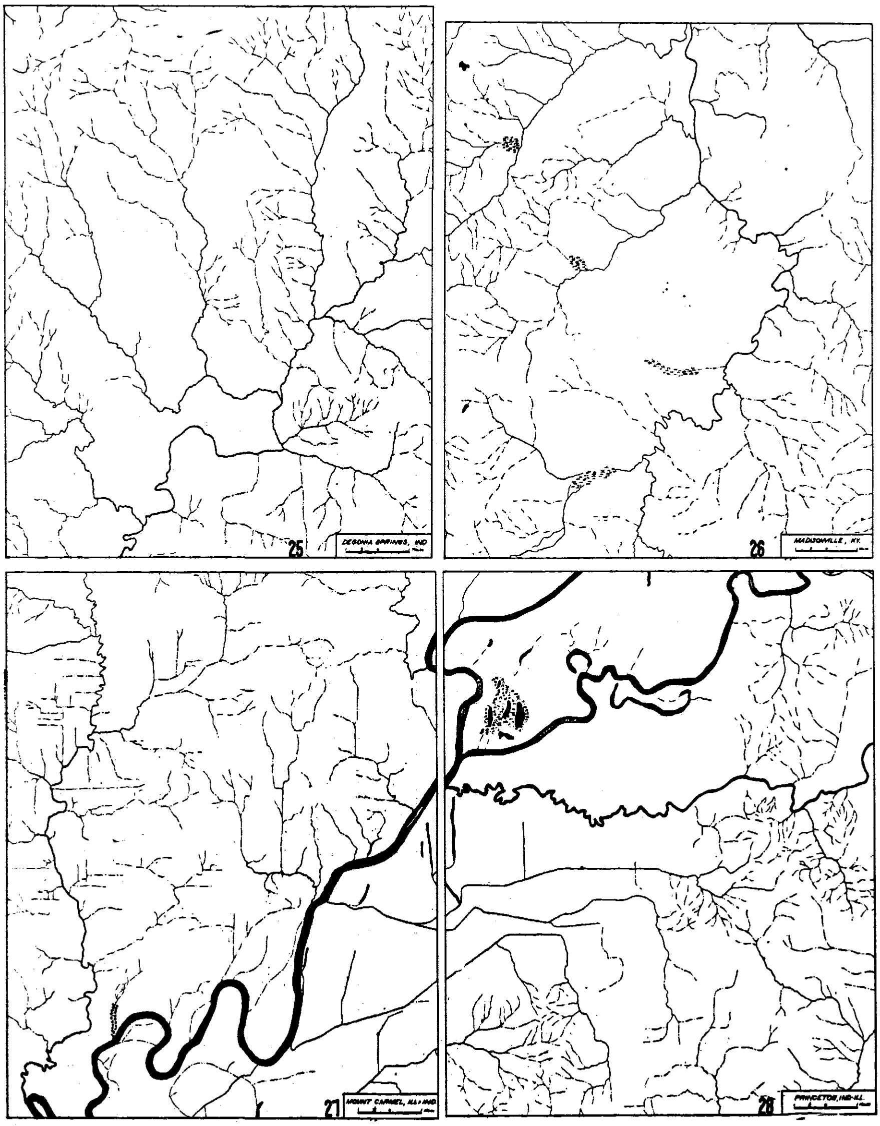


FIG. 25. Integration well started. The emergence of master tributaries.
FIG. 26. Integration rather far along. Abstraction quite evident.
FIG. 27. Rather advanced integration.
FIG. 28. Advanced integration. Master streams and master tributaries.

altitude undoubtedly is a factor[15] in the supply of ground water, but does not appear to apply in the case of the above-mentioned problem since the cycle of intermittency exists in regions of low as well as high elevation.

A study of the dynamic cycle has opened up a highly interesting problem on the relations between ground water and the history of the cycle.

INTEGRATION.

Extension is a time of increasing complexity, integration a time of simplification. The drainage system during integration maintains its control over acquired territory and at the same time consolidates its holdings, as it were, by a marked reduction in the number of tributaries, by the return of intermittent streams, and finally, by the emergence of master streams and master tributaries.

A thorough description and consideration of the detailed phases of integration are very much more difficult tasks than they are for extension because of the paucity of examples on present land surfaces. Some of the activities may be observed in a miniature fashion, but rarely on a large scale. The maps used as illustrations have been chosen to show the sequence of events to the best advantage for the size of the area.

The reappearance of the skeletonized form signalizes the definite existence of integration such as shown in Figure 24. Further progress of the stage appears on Figures 25, 26, 27, and 28, in a sequence which shows continued decrease in the number of streams, the spread of intermittency, and the gradual accentuation of the master tributaries. Figure 26 lies about intermediate in the progress of integration between Figures 24 and 25 and Figures 27 and 28. Of the series, the Princeton map (Figure 28) has progressed the furthest and it is of interest to notice that the Haubstadt map (Figure 24) which adjoins the Princeton on the south occupies a position somewhat more removed from the chief regional streams. The maps reproduced are fairly typical and represent, in rather brief fashion to be sure, several steps in integration. Maps from the lower Mississippi region show too small a section of the drainage system to be of comparative value.

The activities or processes responsible for the progress of integration appear to be abstraction, absorption, and a type of aggression.

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[15]Davis, W. M. Geographical Essays. Boston, 1909. P. 262.

Abstraction.—Gilbert[16] defined the term as follows, "A stream which for any reason is able to corrade its bottom more rapidly than do its neighbors, expands its valley at their expense, and eventually 'abstracts' them." The idea is employed here in exactly the same sense save that the effects of lateral corrasion are also included.

Thus, abstraction is the elimination of tributaries, commonly of the shorter type, by the lateral and vertical migration of the main; it is also the loss of identity and personal independence of a secondary on the meander belt of the primary. The lateral migration constantly increases the immediate drainage area of the master itself at the expense of its tributaries. In this way, the lower part of a tributary system may be dismembered or a tributary may be distinctly shortened so that it ends at the base of the valley wall. An example, indefinite in the sense that it reverses the order of events, is shown on Figure 26 slightly northeast of the center. The main stream appears (on the topographic map) to lie sufficiently below the general valley bottom to permit the origin and growth of several small tributaries. Now, these tributaries in their recent formation illustrate, in reverse order, the elimination of just such streams by lateral swinging in the construction of a flood plain.

The elimination of streams because of vertical migration of the main, if such occurs, belongs properly to the stage of extension and therefore abstraction actually begins during extension but becomes neither predominant nor prominent in the sense here employed until after maximum extension has passed.

Absorption refers to the disappearance of streams permanently or partially probably because of a general flattening of the ground water surface and its consequent depression below the valley bottoms. The first step is the return to intermittency; the second, the complete elimination of the stream save during the immediate discharge of rainfall. Absorption is undoubtedly responsible not only for the disappearance of many small tributaries, but also for the return of intermittency in the whole headwaters area of a drainage system during the progress of integration.

Route to the Sea.—The attempt made by a master stream to secure the shortest valley route to the sea in harmony with

[16]Gilbert, G. K. Report on the geology of the Henry Mountains. U. S. Geog. and Geol. Survey of the Rocky Mtn. Region, Washington, 1877. P. 141.

the regional slope of a subdued or peneplain surface has been called aggression for want of a better name. Since the process depends upon stream activity and upon decreasing environmental control, it is classed under dynamic activities. The laws of flow are ultimately based on gravity and streams therefore desire the shortest route to their outlets, a desire the more nearly fulfilled as factors of environment, except regional slope, relinquish control.

Geological history probably must be called upon for examples. The Delaware, the Susquehanna, and the Potomac were true *integrational consequents* if they took approximately their present courses on a peneplain surface.

Results.—The net results of abstraction and absorption are the elimination of a host of tributaries from the plexus of streams in existence during maximum extension, the simultaneous accentuation of certain streams which finally emerge as master tributaries, and the production of a skeletonized framework just as typical in its way of late integration as the previous skeletal outline was of early extension.

RELATIONSHIPS.

The details in the development of a drainage system, especially those having to do with pattern and behavior, depend upon the nature of the surface, the slope, the material, and the structure. In the present work, adjustments to diverse structures and variable composition have not been considered. Uniformity of material and simplicity of structure have been assumed in order to keep the scheme as near the ideal as possible. The influence of those factors may then be treated as producing variations from the ideal, or simplified, scheme of development.

There is no intention to minimize the importance of land form or the influence of rock structure and lithology. Yet upon strict analysis, rock and structure may modify the valley form or the position of a stream but they can not alter the nature of the dynamic processes or the stream activities. The entire cycle as here outlined may even be considered to belong within the border-land connecting the active and passive phases of physiography. If so, the dynamic cycle has this distinctive feature: its origin is in the geodynamic rather than in the geomorphologic viewpoint.

However that may be, many features characteristic of the pattern of a drainage system depend clearly upon the influence of geologic environment. Stream adjustment is merely one example. A consideration of such environmental influences lies outside the province of the present paper; moreover they have been fully and admirably discussed by others.

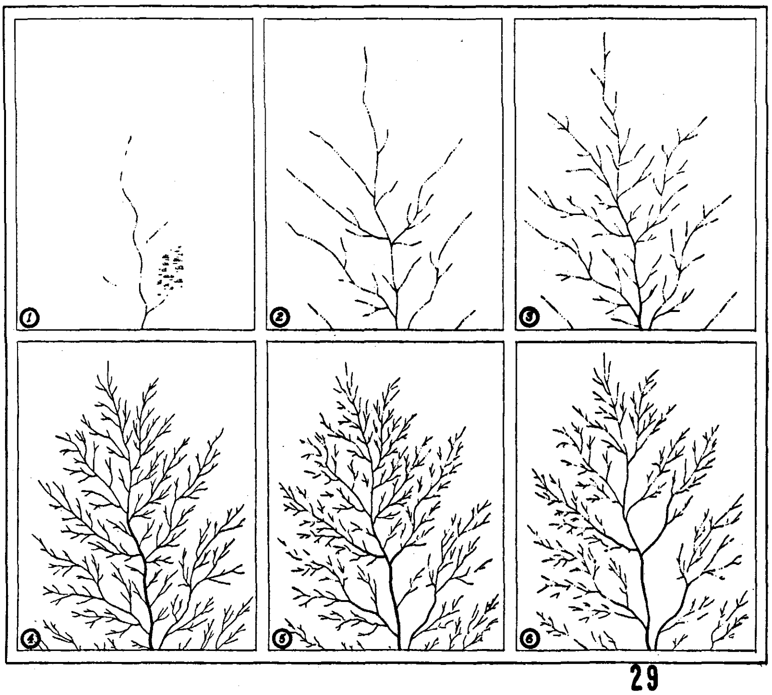

FIG. 29. A summary diagram of the dynamic cycle: (1) initiation, (2) elongation, (3) elaboration, (4) maximum extension, (5) abstraction and absorption during integration, and (6) the emergence of master tributaries.

It will have been noticed that practically all of the illustrations have been taken from the humid portion of the United States. A drier climate undoubtedly would result in the following features in contrast with those described above: a great increase of intermittency; somewhat retarded elongation; poorly developed elaboration; a more skeletonized form at maximum extension; and an accentuation of the absorption process. On the whole the drainage system would be retarded in rate of development and would never attain the complex elaboration characteristic of a system under a humid climate.

Highly pervious rocks would have the same effect in some respects as a dry climate.

SUMMARY.

Figure 29 is an ideal summary of the dynamic cycle.

Classification is a matter of convenience, an expedient permitting us in many instances to grasp certain concepts and to transfer them to others. The drainage cycle actually knows no distinct subdivisions, although it does divide itself into general stages governed by certain prominent characteristics. Phases akin to extension may extend far into integration; and integration may begin its activities locally early in extension. The drainage system taken throughout its cyclic history reveals no sharp boundaries, no lines of cleavage where one set of characteristics ends and another begins. Only a preponderance of process or activity justifies the privilege of classification.

The dynamic cycle includes the history of a drainage system from initiation through the stages of extension and integration, or to the event whereby initiation begins anew. Strictly, the dynamic cycle refers to a series of events repeated cyclically and characterized by two sets of activities of which one set dominates extension and the other dominates integration. Diastrophism not only motivates the cycle but also initiates or interrupts it. Climate apparently regulates the intensity of the extensional activities, elongation and especially elaboration. The relations between climate and ground water must bear directly upon the very nature of the cycle itself. If so, several interesting problems await solution.

At the beginning of extension initial streams are elongated and the system is elaborated by the addition of tributaries of constantly decreasing importance until the fully developed branch-work occupies the basin blocked out originally by the elongated streams when they first made drainage contact with adjoining systems. Abbreviated streams and the skeletonized form have disappeared at maximum extension which, expressed more precisely, is attained when the so-called drainage ratio reaches a maximum. Intermittency has at the same time decreased to zero.

Integration in a measure reverses the processes of extension, for abstraction and absorption eliminate tributaries until merely a skeletonized framework remains to care for drainage.

Intermittency returns and spreads progressively among the tributaries. During the final phases of integration so far recognized emphasis is placed upon certain members of the system whereby master tributaries come to dominate the ultimate skeletal system, and the trunk stream seeks the shortest valley route to a point of discharge consistent with regional slope. The cycle may then be repeated or else terminated in accordance with subsequent diastrophism.

Extension is a time of conquest and minute invasion; integration a time of withdrawal and consolidation. In the whole story the rôle of climate, ground water, the drainage-ratio factor, and their mutual relationships appear to be of paramount importance in the evolution of the dynamic cycle.